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(54) **ENERGY RECOVERY SNUBBER CIRCUIT
FOR POWER CONVERTERS**

4,563,731 A 1/1986 Sato et al.
4,645,278 A 2/1987 Yevak et al.
4,712,160 A 12/1987 Sato et al.

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(Continued)

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FOREIGN PATENT DOCUMENTS

JP 4217869 A 8/1992
JP 10243640 A 9/1998

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patent is extended or adjusted under 35
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(Continued)

OTHER PUBLICATIONS

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Texas Instrument, Control Driven Synchronous Rectifiers in Phase
Shifted Full Bridge Converters, Mar. 2003, Texas Instruments.*

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USPC **363/24**; 363/17; 363/21.06; 363/21.14;
363/25; 363/26; 363/56.05; 363/56.07

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(56) **References Cited**

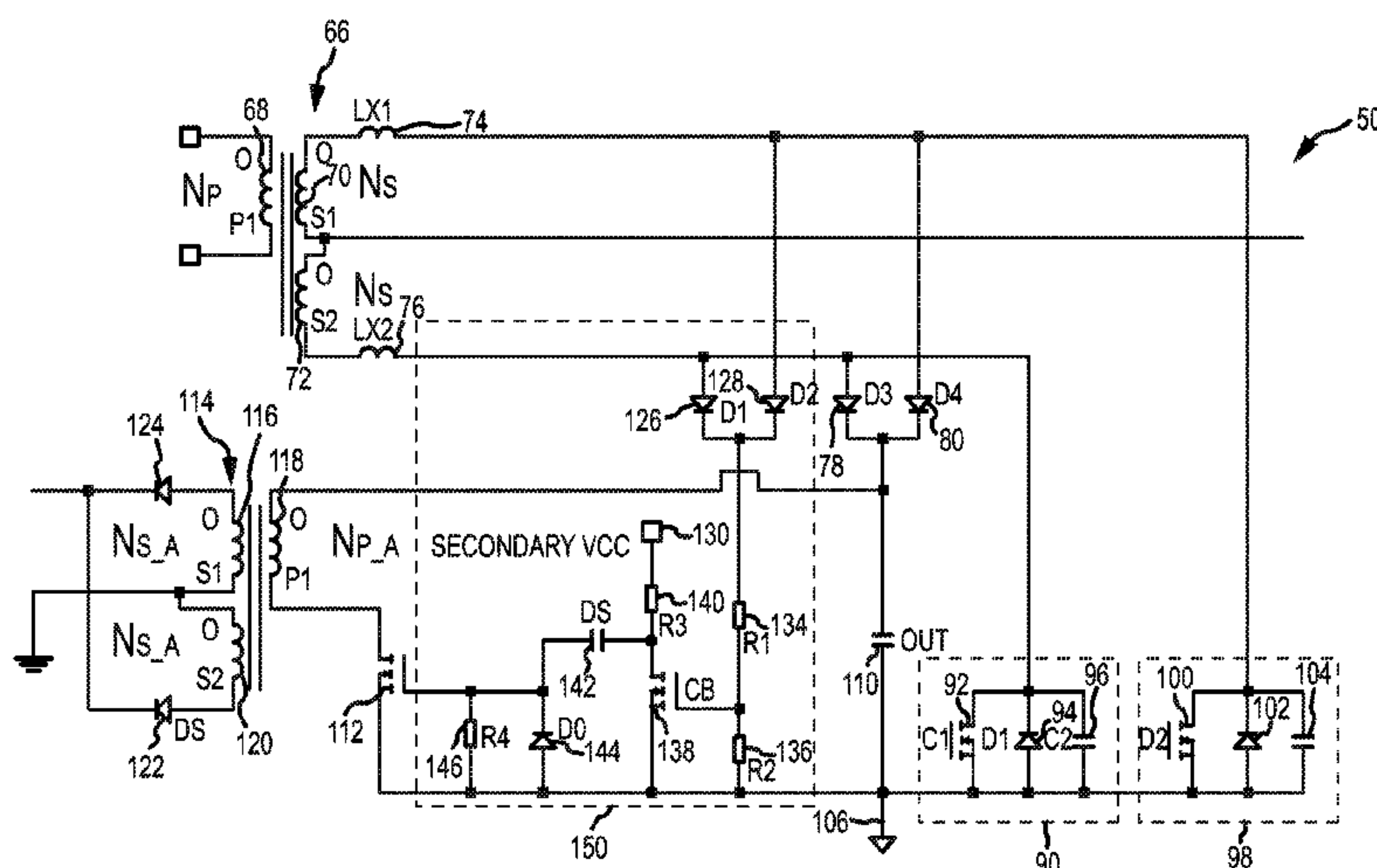
U.S. PATENT DOCUMENTS

4,273,406 A 6/1981 Okagami
4,370,703 A 1/1983 Risberg

(57) **ABSTRACT**

An energy recovery snubber circuit for use in switching
power converters. The power converters may include a switch
network coupled to a primary winding of an isolation trans-
former, and rectification circuitry coupled to a secondary
winding of the isolation transformer. The energy recovery
snubber circuit may include clamping circuitry that is opera-
tive to clamp voltage spikes and/or ringing at the rectification
circuitry. The clamped voltages may be captured by an energy
capture module, such as a capacitor. Further, the energy
recovery snubber circuitry may include control circuitry
operative to return the energy captured by the energy capture
module to the input of the power converter. To maintain
electrical isolation between a primary side and a secondary
side of the isolation transformer, a second isolation trans-
former may be provided to return the captured energy back to
the input of the power converter.

21 Claims, 6 Drawing Sheets



(56)

References Cited**U.S. PATENT DOCUMENTS**

4,788,626 A 11/1988 Neidig et al.
 4,806,110 A 2/1989 Lindeman
 4,841,220 A 6/1989 Tabisz et al.
 4,857,822 A 8/1989 Tabisz et al.
 4,866,367 A 9/1989 Ridley et al.
 4,890,217 A 12/1989 Conway
 4,893,227 A 1/1990 Gallios et al.
 4,899,256 A 2/1990 Tin et al.
 4,901,069 A 2/1990 Veneruso
 5,065,302 A 11/1991 Kanazawa
 5,090,919 A 2/1992 Tsuji
 5,101,322 A 3/1992 Ghaem et al.
 5,132,890 A 7/1992 Blandino
 5,235,491 A 8/1993 Weiss
 5,325,283 A 6/1994 Farrington
 5,351,182 A * 9/1994 Miyazaki et al. 363/132
 5,365,403 A 11/1994 Vinciarelli et al.
 5,373,432 A 12/1994 Vollin
 5,442,540 A 8/1995 Hua
 5,673,185 A 9/1997 Albach et al.
 5,712,772 A 1/1998 Telefus et al.
 5,786,992 A 7/1998 Vinciarelli et al.
 5,790,395 A 8/1998 Hagen
 5,811,895 A 9/1998 Suzuki et al.
 5,838,554 A 11/1998 Lanni
 5,859,771 A 1/1999 Kniegl
 5,898,581 A * 4/1999 Liu 363/53
 5,905,369 A 5/1999 Ishii et al.
 5,923,543 A 7/1999 Choi
 5,949,672 A 9/1999 Bertnet
 5,978,238 A * 11/1999 Liu 363/56.09
 6,009,008 A 12/1999 Pelly
 6,091,611 A 7/2000 Lanni
 6,128,206 A * 10/2000 Sun et al. 363/127
 6,183,302 B1 2/2001 Daikuhara et al.
 6,191,957 B1 2/2001 Peterson
 6,272,015 B1 8/2001 Mangtani
 6,275,397 B1 8/2001 McClain
 6,307,761 B1 10/2001 Nakagawa
 6,323,627 B1 11/2001 Schmiederer et al.
 6,385,059 B1 5/2002 Telefus et al.
 6,388,897 B1 5/2002 Ying et al.
 6,390,854 B2 5/2002 Yamamoto et al.
 6,396,716 B1 5/2002 Liu et al.
 6,452,816 B2 9/2002 Kuranki
 6,459,175 B1 10/2002 Potega
 6,487,098 B2 11/2002 Malik et al.
 6,549,409 B1 4/2003 Saxelby et al.
 6,578,253 B1 6/2003 Herbert
 6,721,192 B1 4/2004 Yang et al.
 6,775,162 B2 8/2004 Mihai et al.
 6,894,461 B1 5/2005 Hack et al.
 6,919,715 B2 7/2005 Muratov et al.
 6,989,997 B2 1/2006 Xu
 7,035,126 B1 4/2006 Lanni
 7,038,406 B2 5/2006 Wilson
 7,102,251 B2 9/2006 West
 7,139,180 B1 11/2006 Herbert
 7,202,640 B2 4/2007 Morita
 7,208,833 B2 4/2007 Nobori et al.
 7,212,420 B2 5/2007 Liao
 7,239,532 B1 7/2007 Hsu et al.
 7,274,175 B2 9/2007 Manolescu
 7,315,460 B2 1/2008 Kyono
 7,386,286 B2 6/2008 Petrovic et al.
 7,450,388 B2 11/2008 Beihoff et al.
 7,564,706 B1 7/2009 Herbert
 7,596,007 B2 9/2009 Phadke et al.
 7,701,305 B2 4/2010 Lin et al.
 7,830,684 B2 * 11/2010 Taylor 363/52
 7,924,578 B2 4/2011 Jansen et al.
 8,059,434 B2 11/2011 Huang et al.
 8,102,678 B2 1/2012 Jungreis
 8,125,181 B2 2/2012 Gregg et al.
 8,126,181 B2 2/2012 Yamamoto et al.

8,134,848 B2 3/2012 Whittam et al.
 8,155,368 B2 4/2012 Cheung et al.
 8,194,417 B2 6/2012 Chang
 8,207,717 B2 6/2012 Uruno et al.
 8,243,472 B2 8/2012 Chang et al.
 8,344,689 B2 1/2013 Boguslavskij
 8,369,111 B2 2/2013 Balakrishnan et al.
 8,400,801 B2 3/2013 Shinoda
 2002/0008963 A1 1/2002 Dibene et al.
 2002/0011823 A1 1/2002 Lee
 2002/0036200 A1 3/2002 Ulrich et al.
 2003/0035303 A1 2/2003 Balakrishnan et al.
 2003/0112645 A1 6/2003 Schlecht
 2004/0183510 A1 9/2004 Sutardja et al.
 2004/0252529 A1 12/2004 Huber et al.
 2005/0024016 A1 2/2005 Breen et al.
 2005/0036338 A1 2/2005 Porter et al.
 2005/0117376 A1 6/2005 Wilson
 2005/0138437 A1 6/2005 Allen et al.
 2005/0194942 A1 9/2005 Hack et al.
 2005/0225257 A1 10/2005 Green
 2005/0254268 A1 11/2005 Reinhard et al.
 2006/0002155 A1 1/2006 Shteynberg et al.
 2006/0022637 A1 2/2006 Wang et al.
 2006/0152947 A1 7/2006 Baker et al.
 2006/0213890 A1 9/2006 Kookan et al.
 2006/0232220 A1 10/2006 Melis
 2007/0040516 A1 2/2007 Chen
 2007/0120542 A1 5/2007 LeMay
 2007/0121981 A1 5/2007 Koh et al.
 2007/0138971 A1 6/2007 Chen
 2007/0247091 A1 10/2007 Maiocchi
 2007/0263415 A1 11/2007 Jansen et al.
 2008/0018265 A1 1/2008 Lee et al.
 2008/0043496 A1 2/2008 Yang
 2008/0191667 A1 8/2008 Kernahan et al.
 2009/0034299 A1 2/2009 Lev
 2009/0045889 A1 2/2009 Goergen et al.
 2009/0196073 A1 8/2009 Nakahori
 2009/0290384 A1 11/2009 Jungreis
 2009/0300400 A1 12/2009 DuBose
 2010/0039833 A1 2/2010 Coulson et al.
 2010/0289466 A1 11/2010 Telefus et al.
 2010/0317216 A1 12/2010 Pocrass
 2010/0322441 A1 12/2010 Weiss et al.
 2011/0132899 A1 6/2011 Shimomugi et al.
 2011/0261590 A1 10/2011 Liu
 2012/0112657 A1 5/2012 Van Der Veen et al.

FOREIGN PATENT DOCUMENTS

JP 2000083374 A 3/2000
 JP 20000253648 A 9/2000
 JP 2004208357 A 7/2004

OTHER PUBLICATIONS

EE Times.com—"Team Claims Midrange Wireless Energy Transfer", by R. Colin Johnson, 4 pages, Nov. 6, 2007.
 EE Times. com—"Wireless Beacon Could Recharge Consumer Devices", by R. Colin Johnson, 3 pages, Nov. 6, 2007.
 Novel Zero-Voltage and Zero-Current Switching (ZVZCS) Full Bridge PWM converter Using Coupled Output Inductor, Sep. 2002 IEEE, pp. 641-648.
 "New Architectures for Radio-Frequency dc/dc Power Conversion", Juan Rivas et al., Laboratory for Electromagnetic and Electronic Systems, Jan. 2004, Massachusetts Institute of Technology, Room 10-171 Cambridge, MA 02139, pp. 4074-4084.
 "Randomized Modulation in Power Electronic Converters". Aleksander M. Stankovic, member IEEE, and Hanoch Lev-Ari, vol. 90, No. 5, May 2002, pp. 782-799.
 "Analysis and Special Characteristics of a Spread-Spectrum Technique for Conducted EMI Suppression", K.K. tse, et al. Member IEEE, IEEE Transactions on Power Electronics, vol. 15., No. 2, Mar. 2000, pp. 399-410.

* cited by examiner

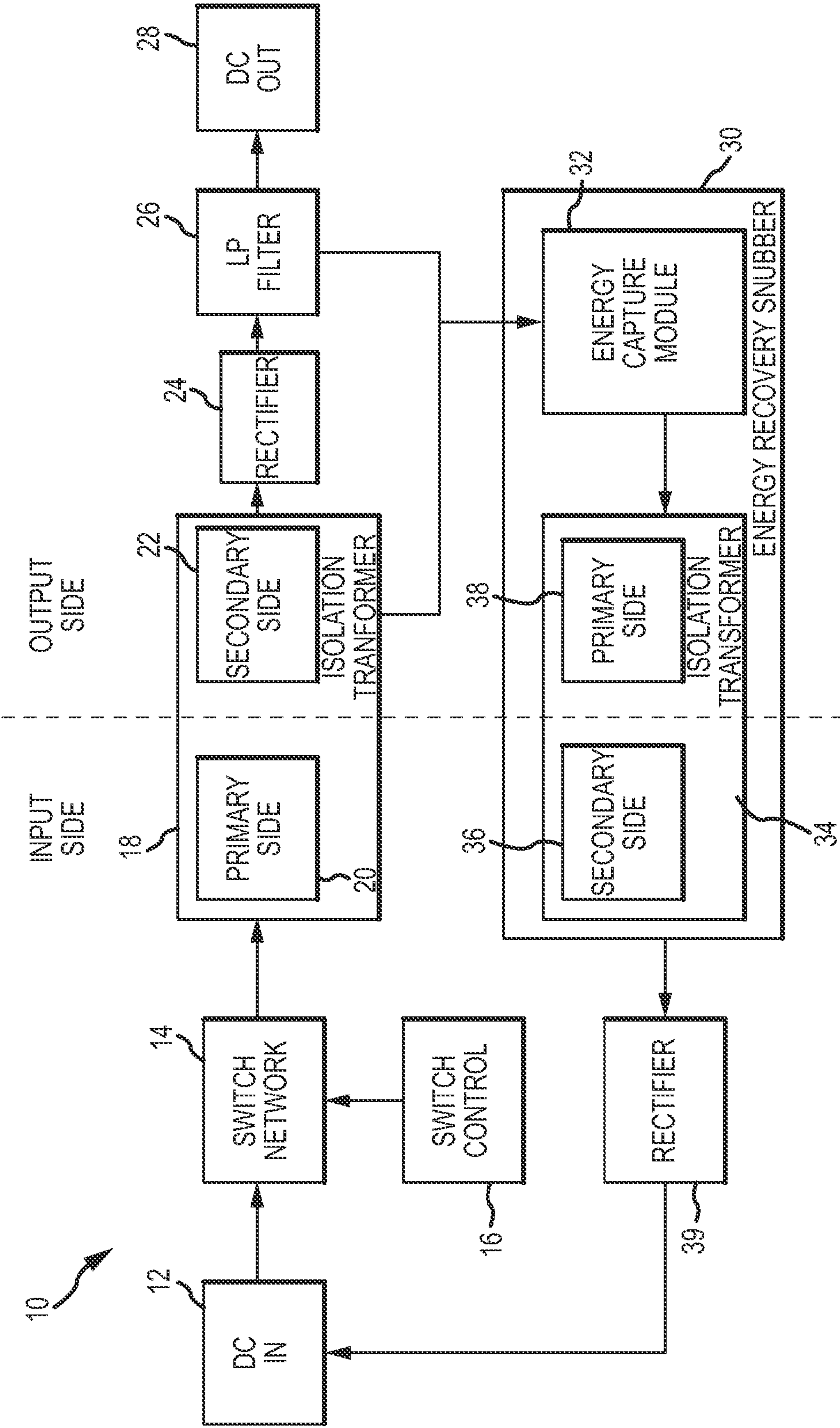
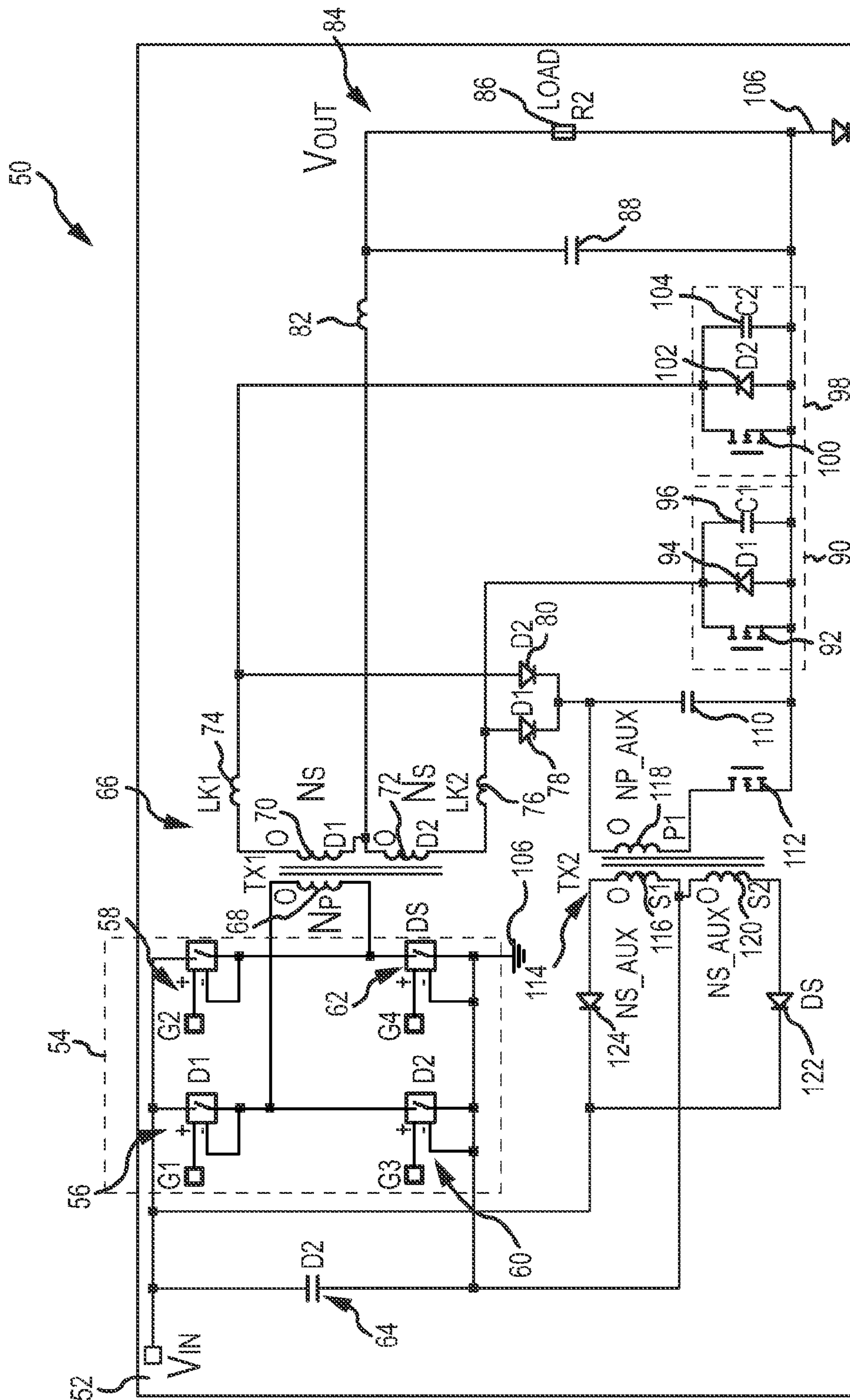


FIG.1



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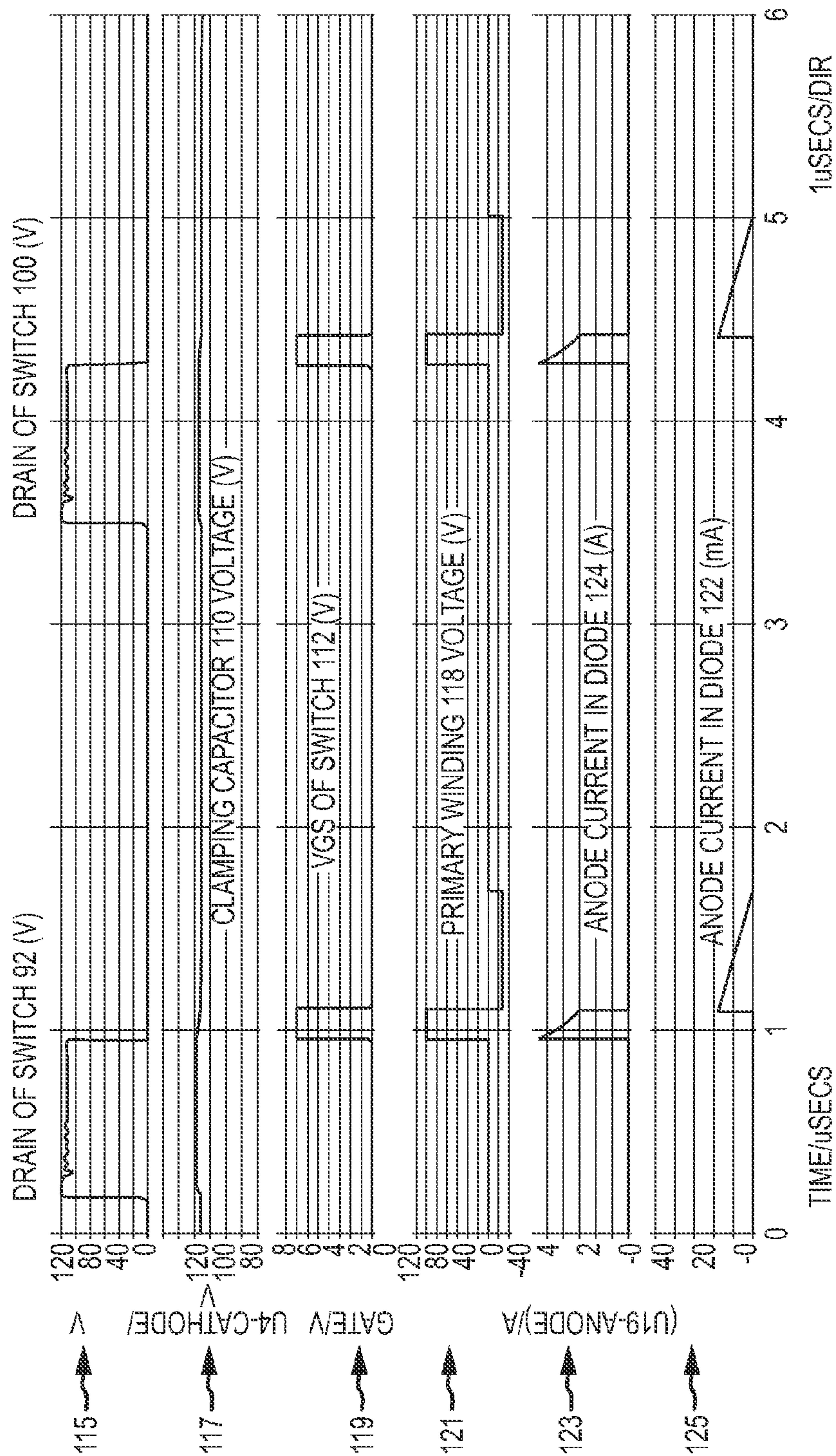


FIG.3

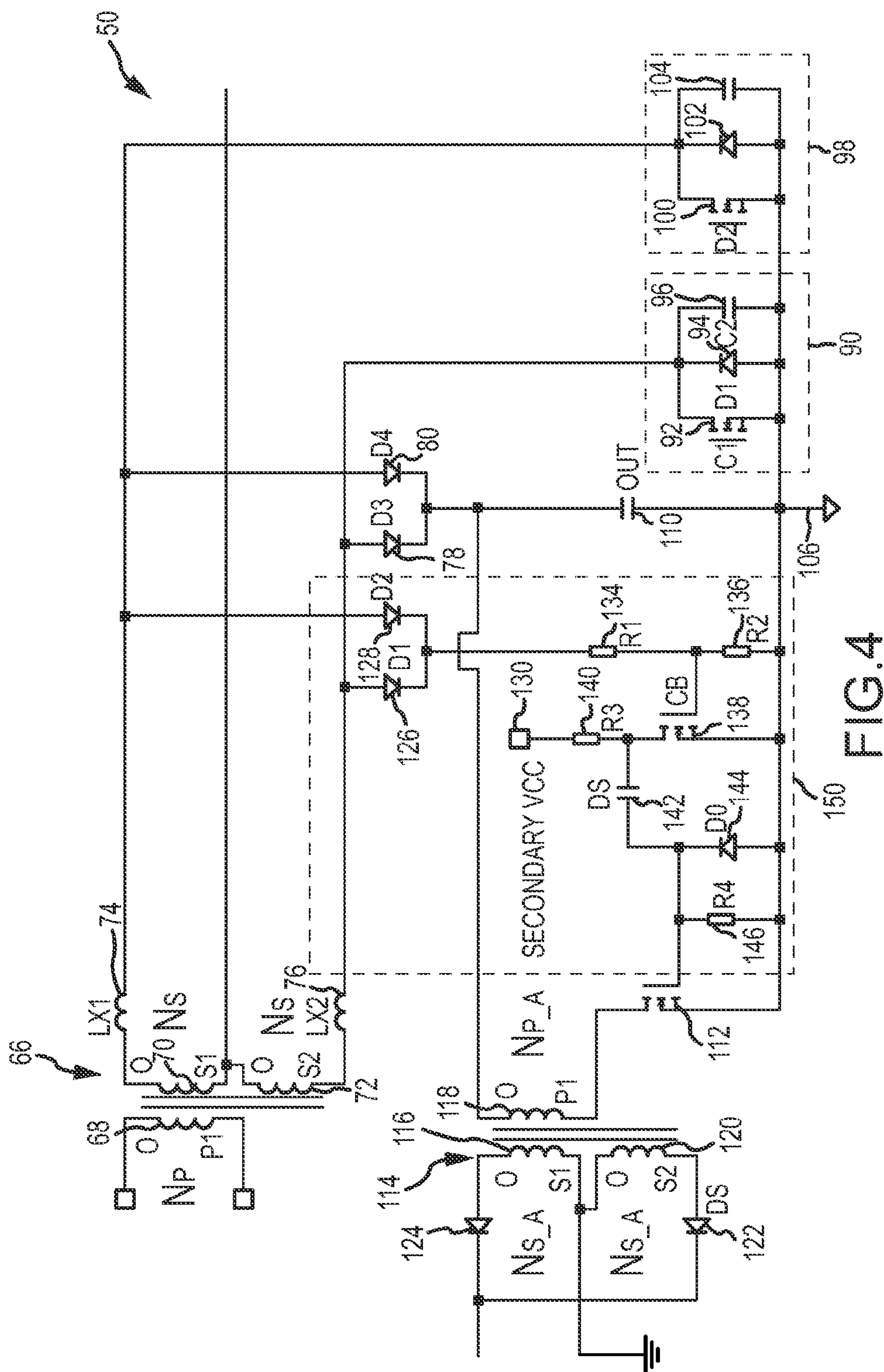


FIG. 4

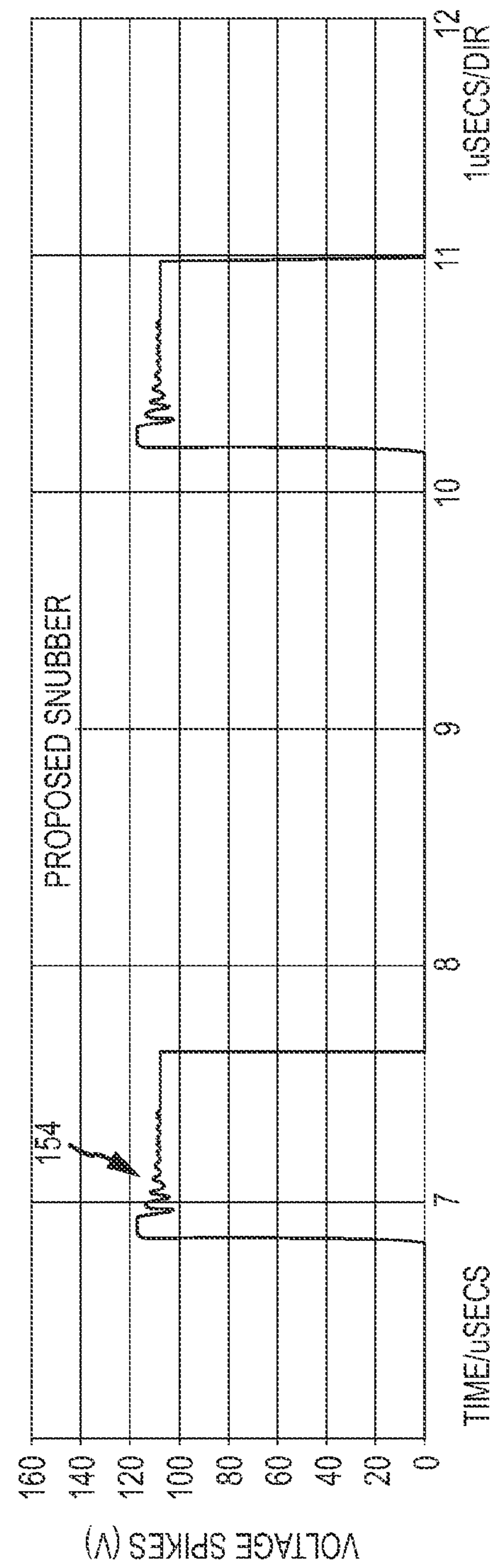
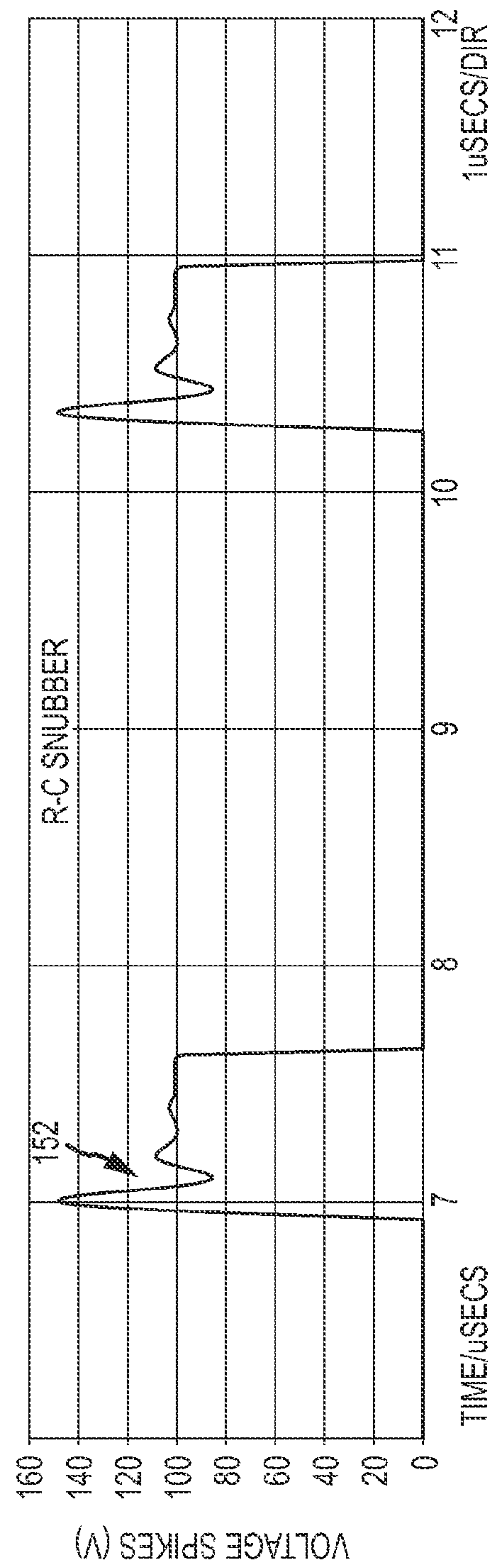
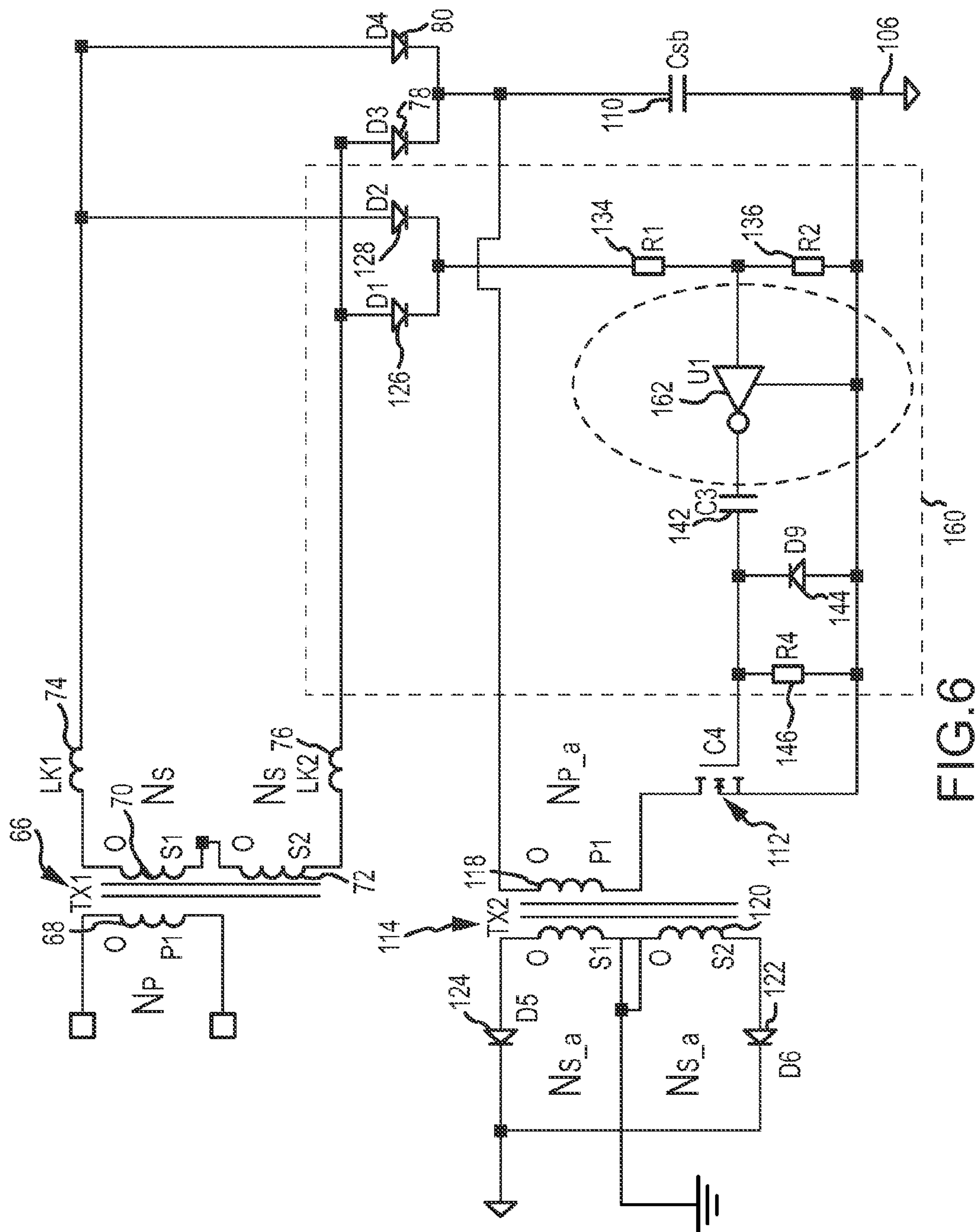


FIG.5



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**ENERGY RECOVERY SNUBBER CIRCUIT
FOR POWER CONVERTERS****CROSS-REFERENCE TO RELATED
APPLICATION**

This application claims priority under 35 U.S.C. 119 to U.S. Provisional Application No. 61/176,273, entitled: "ENERGY RECOVERY SNUBBER CIRCUIT FOR POWER CONVERTERS," filed on May 7, 2009, the contents of which are incorporated herein as if set forth in full.

BACKGROUND

Generally, a power converter is a power processing circuit that converts an input voltage or current source into a specified output voltage or current. Power converters are used in numerous types of applications including computers, audio/video equipment, mobile electronic devices, power systems, and the like.

One type of power converter, known as a DC/DC power converter, is operative to convert an input voltage waveform having a DC component into an output DC voltage waveform which may be at a different voltage level than the input voltage waveform. For various reasons, it is often desirable for the input to be electrically isolated from the output of the power converter. To accomplish this, an isolation transformer may be used, which may the input DC voltage to be "chopped" into an AC voltage. Further, in order to perform the waveform conversion from an AC output of the isolation transformer to a DC output voltage, rectification circuitry may be used. Traditionally, rectification circuitry included one or more diodes coupled to the secondary side of the isolation transformer. Since diodes only conduct current when they are forward biased, they may be used to convert the AC voltage from the isolation transformer to an output DC voltage. Alternatively, the rectification circuitry may include synchronous rectifiers that utilize transistor switches that are selectively turned on and off synchronous with the AC signal being rectified in order to control the conduction of current from the isolation transformer to the rectifier output.

The increasing computational speeds and densities of integrated circuits (ICs) have led to a reduction of their operating voltages. This reduction of operating voltages requires DC/DC converters to provide higher output current to achieve similar power output. As the output voltage is decreased and the output current is increased, the power loss incurred by the output rectifiers becomes a dominant factor for the efficiency of the power converter.

In order to allow the use of relatively small energy storage elements and filtering components (e.g., capacitors, inductors, transformers, and the like), the switching devices associated with the power converter may be switched at a relatively high frequency (e.g., a few hundred kilohertz). However, this high frequency switching may cause large voltage spikes and high frequency ringing at the output rectification circuitry. The voltage spikes and high frequency ringing may generally be caused by the parasitic or leakage inductance of the isolation transformer and the parasitic capacitance of the rectification diodes or transistor switches.

The voltage spikes and high frequency ringing are undesirable for several reasons. For example, the high voltage spikes may require the use of rectification devices that are rated for high voltages, which may be costly and larger in size. Further, the use of high voltage rated devices may reduce the efficiency of the power converter because those devices may have relatively high conduction losses. Additionally, the

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energy transmitted by the high frequency ringing and high voltage potentials may induce electromagnetic interference (EMI) problems in the various components of the power converter or other surrounding components.

To deal with this problem, various passive and active snubber or clamping circuits have been developed to compensate for the above-noted undesirable properties. These circuits generally have one or more shortcomings that may include increased costs and/or reduced efficiency of the power converter.

It is against this background that the energy recovery snubber circuits for power converters described herein have been invented.

SUMMARY

Disclosed is an energy recovery snubber circuit for use in a switching power converter having an input and an output, the power converter including a first transformer having a primary winding and a secondary winding, a controllable switch coupled to the primary winding, and rectification circuitry coupled to the secondary winding. The energy recovery snubber circuit includes a voltage clamping element coupled to the rectification circuitry; a capacitive element coupled to the voltage clamping element for storing energy captured by the voltage clamping element; a second transformer having a primary winding coupled to the capacitive element and a secondary winding coupled to the input of the power converter; and control circuitry that is operative to selectively cause the transfer of energy stored by the capacitive element to the input of the power converter via the second transformer.

The power converter may include a low-pass filter at the output thereof. The low-pass filter may include an output inductor and an output capacitor. The energy recovery snubber circuit may include a rectifier coupled to the secondary winding of the energy recovery snubber circuit.

The voltage clamping element may include a rectifying switch. The rectifying switch may include a MOSFET. The voltage clamping element may include an inverter.

The controllable switch may include four different switches, two of which are on at a time, one pair of which are on while the other pair is off and one pair of which is off while the other pair is on. The voltage clamping element may include a first and a second rectifying switch, one of which is on at a time, the first rectifying switch being on when the one pair of switches in the controllable switch are on and the second rectifying switch being on when the other pair of switches in the controllable switch are on. The first and second rectifying switches may each include a MOSFET.

Also disclosed is a switching power converter having an input and an output. The power converter includes a first transformer having a primary winding and a secondary winding; a controllable switch coupled to the primary winding; rectification circuitry coupled to the secondary winding; and an energy recovery snubber circuit for the switching power converter. The energy recovery snubber circuit includes a voltage clamping element coupled to the rectification circuitry; a capacitive element coupled to the voltage clamping element for storing energy captured by the voltage clamping element; a second transformer having a primary winding coupled to the capacitive element and a secondary winding coupled to the input of the power converter; and control circuitry that is operative to selectively cause the transfer of energy stored by the capacitive element to the input of the power converter via the second transformer.

The power converter may include a low-pass filter at the output thereof. The low-pass filter may include an output

inductor and an output capacitor. The energy recovery snubber circuit may include a rectifier coupled to the secondary winding of the energy recovery snubber circuit.

The voltage clamping element may include a rectifying switch. The rectifying switch may include a MOSFET. The voltage clamping element may include an inverter.

The controllable switch may include four different switches, two of which are on at a time, one pair of which are on while the other pair is off and one pair of which is off while the other pair is on. The voltage clamping element may include a first and a second rectifying switch, one of which is on at a time, the first rectifying switch being on when the one pair of switches in the controllable switch are on and the second rectifying switch being on when the other pair of switches in the controllable switch are on. The first and second rectifying switches may each include a MOSFET.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 illustrates a block diagram of a DC/DC power converter that includes an exemplary energy recovery snubber circuit.

FIG. 2 illustrates a schematic diagram of a DC/DC power converter that includes an exemplary energy recovery snubber circuit.

FIG. 3 illustrates various waveforms associated with the operation of the DC/DC power converter shown in FIG. 2.

FIG. 4 illustrates an exemplary energy recovery snubber circuit.

FIG. 5 illustrates voltage waveforms for rectification circuitry used in DC/DC power converters.

FIG. 6 illustrates another exemplary energy recovery snubber circuit.

DETAILED DESCRIPTION

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof have been shown by way of example in the drawings and are herein described in detail. It should be understood, however, that it is not intended to limit the invention to the particular form disclosed, but rather, the invention is to cover all modifications, equivalents, and alternatives falling within the scope and spirit of the invention as defined by the claims.

FIG. 1 illustrates a block diagram of a DC/DC power converter 10 that includes an exemplary energy recovery snubber 30. The power converter 10 may be operative to convert a DC voltage from a DC input node 12 into an output DC voltage at a DC output node 28. The power converter 10 may include an isolation transformer 18 having one or more primary side windings 20 coupled to the DC input node 12 and one or more secondary side windings 22 coupled to the DC output node 28. To provide an AC voltage to the primary winding 20 of the isolation transformer 18, a switch network 14 including one or more switches may be coupled between the primary winding 20 and the DC input node 12. The switch network 14 may be controlled by a switch control module 16 that is operative to turn the switches of the switch network 14 on and off to provide an AC voltage to the primary winding 20 of the isolation transformer 18. As an example, the switch network 14 may include a half bridge network, a full bridge network, or the like.

Rectification circuitry 24 may be coupled to the one or more secondary windings 22 of the isolation transformer 18 to provide a rectified voltage waveform. The rectification circuitry 24 may include one or more diodes, one or more synchronous rectifiers (e.g., transistor switches), or the like.

The rectified voltage waveform may then be smoothed by a low pass (LP) filter 26, such that a DC voltage appears at the DC output node 28, which in turn may be coupled to a load. The LP filter 26 may include one or more capacitors, inductors, or other passive or active components.

To reduce the high voltage spikes and high frequency ringing caused by the high frequency switching of the switch network 14 and its effect on the leakage inductance of the isolation transformer 18 and the rectification circuitry 24, the energy recovery snubber 30 may be provided. Functionally, the energy recovery snubber 30 may include an energy capture module 32 that may operate to capture energy that causes the undesirable behavior (e.g., ringing and voltage spikes) at the rectification circuitry 24. In this regard, the rectification circuitry 24 may be designed such that its components are not required to withstand extreme voltage conditions, which may reduce the cost of the power converter 10 while increasing its efficiency.

In addition to capturing the energy, the energy recovery snubber 30 may be operative to return the captured energy to the DC input node 12, which may substantially improve the efficiency of the power converter 10. To return the captured energy to the DC input node 12 and to preserve the electrical isolation between the primary side and secondary side of the power converter 10, the energy recovery snubber 30 may include an isolation transformer 34 having one or more primary side windings 38 and one or more secondary side windings 34. In operation, the energy captured by the energy capture module 32 may be transferred across the isolation transformer 34, where it may be rectified by a rectifier 39, and returned to the DC input node 12. In this regard, the energy that is normally wasted by the leakage inductance of the isolation transformer 18 and the parasitic capacitance of the rectification circuitry 24 may be recovered or recycled by the power converter 10, thereby improving the efficiency of the power converter 10 while reducing the high voltage spikes and high frequency ringing on the rectification circuitry 24.

FIG. 2 illustrates a schematic diagram of a full bridge DC/DC power converter 50 that includes an exemplary energy recovery snubber circuit. The power converter 50 includes an isolation transformer 66 that is coupled to an input node 52 (V_{in}) via a switch network 54. The switch network includes switches 56, 58, 60, and 62 which may be any suitable type of switches including MOSFETs, IGBTs, or the like. The switches 56, 58, 60, and 62 may be controlled by a switch controller (not shown in FIG. 2) to provide an AC voltage to a primary winding 68 of the transformer 66. In operation, the switches 56 and 62 may conduct for a period of time such that positive V_{in} voltage potential is applied across the primary winding 68 of the transformer 66. During this time, switches 58 and 60 are open (i.e., not conducting). Next, the switch controller may control the switches 56 and 62 to be non-conducting, while the switches 58 and 60 are conducting. As can be appreciated, this has the effect of applying a negative V_{in} voltage potential across the primary winding 68 of the transformer 66. In this regard, the switch controller may selectively control the switches 56, 58, 60, and 62 to apply an AC voltage to the primary winding 68 that swings between positive V_{in} and negative V_{in} voltage potentials.

The power converter 50 also includes synchronous rectifiers 90, 98 that are coupled to outer taps of secondary windings 70, 72 of the isolation transformer 66. In this example, the synchronous rectifiers 90, 98 include MOSFETs 92, 100, respectively. Further, body diodes 94, 102 and capacitors 96, 104 are illustrated to show the characteristics (i.e., equivalent circuits) of the MOSFETs 92, 100, respectively, and are not separate components in the circuit.

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In operation, the gates of the MOSFETS **92**, **100** are controlled by a rectification controller (not shown) to cause the MOSFETS **92**, **100** to conduct at certain distinct times such that energy from the primary winding **68** of the isolation transformer **66** may be transferred to a load **86**. More specifically, when the switches **56** and **62** are conducting, the MOSFET **92** should be conducting. Similarly, when the switches **58** and **60** are conducting, the MOSFET **100** should be conducting. In this regard, the energy from the secondary windings **70**, **72** of the isolation transformer **66** may be rectified. In this example, the MOSFETS **92**, **100** are used for rectification instead of rectification diodes because of their relatively low resistance they exhibit when conducting, which has the effect of minimizing the losses associated with the rectification circuitry.

To provide a stable DC voltage to the output node **84** (V_{out}) of the power converter **50**, a low pass filter that includes an output inductor **82** and an output capacitor **88** may be provided. The values for the inductor **82** and the capacitor **88** may be chosen such that the voltage V_{out} is approximately a DC voltage when the power converter **50** is coupled to the load **86**.

As noted above, high frequency ringing and voltage spikes may be generated due to the fast transitioning of the rectifiers (i.e., the MOSFETS **92**, **100**) from a conducting stage to a non-conducting stage. These undesirable characteristics are mainly due to resonance between the leakage inductance of the isolation transformer **66** (shown schematically as leakage inductors **74** and **76**) and the parasitic capacitance between the drain and source terminals of the rectifiers **90**, **98** (shown schematically as capacitors **96**, **104**, respectively).

To reduce or eliminate the high voltage spikes and ringing that occurs when the MOSFETS **92**, **100** are turned off, clamping diodes **78**, **80** are provided which have their respective anode terminals coupled to the outside ends of the secondary windings **72**, **74** of the isolation transformer **66**, and having their cathode terminals coupled to a first plate of a clamping capacitor **110**.

The clamping diodes **78**, **80** may be any type of suitable diodes. For example, the clamping diodes **78**, **80** may be Schottky diodes in order to provide a relatively small forward bias voltage drop. The clamping capacitor **110** may be relatively large (e.g., 30 nF, 60 nF, 220 nF, or more) such that any voltage spikes or ringing that appear at the outside ends of the secondary windings **72**, **74** (or equivalently, at the drain terminals of the MOSFETS **92**, **100**) are absorbed by the clamping capacitor **110**. As can be appreciated, the voltage appearing across the clamping capacitor **110** is substantially a DC voltage that has an amplitude that is approximately the input voltage V_{in} multiplied by the turns ratio of the isolation transformer **66**.

In addition to the clamping capacitor **110** and the clamping diodes **78**, **80** acting to clamp excessive voltage spikes and ringing, the energy absorbed by the clamping capacitor **110** may also be recycled back to the input node **52** of the power converter **50**. To achieve this functionality, the clamping capacitor **110** may be coupled to a ground potential **106** in parallel with a primary winding **118** of an isolation transformer **114** and a MOSFET **112**. The transformer **114** may include two secondary windings **116**, **120** that each have one end couple to a ground node **106** on the primary side of the power converter **50** and the other end to the input node **52** through rectifying diodes **124**, **122**, respectively.

In operation, the MOSFET **112** may be selectively turned on and off by control circuitry (not shown in FIG. 2; see a control circuit **150** shown in FIG. 4 and a control circuit **160** shown in FIG. 6) coupled to its gate terminal. When the MOSFET **112** is turned on by the control circuitry, current

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will flow from the clamping capacitor **110** through the primary winding **118** of the transformer **114**, inducing a voltage across the primary winding **118**. This voltage will in turn induce a voltage in the secondary winding **116**, which may cause current to flow through the rectifying diode **124** to the input node **52**, where the energy may be stored by an input capacitor **64**. Additionally, when the MOSFET **112** is subsequently opened or turned off, the energy stored in the primary winding **118** will cause a negative voltage across the secondary winding **120**, thereby causing current to flow through the rectifying diode **122** to the input node **52**. In this regard, the energy captured by the clamping capacitor **110** is transferred back to the input source, such that the energy loss of the power converter **50** is substantially reduced.

FIG. 3 illustrates various waveforms associated with the operation of the DC/DC power converter **50** shown in FIG. 2. In particular, the waveform **115** illustrates the voltage between the drain and the source terminals of the MOSFETS **92** and **100**. As can be seen, the voltage across the MOSFETS **92**, **100** rises sharply as they transition from a conducting stage to a non-conducting stage, and falls again as they transition back to a conducting stage. The waveform **117** illustrates the voltage across the clamping capacitor **110**. The waveform **119** illustrates the voltage between the gate and source terminals (V_{gs}) of the MOSFET **112**, which may be controlled by control circuitry (see the control circuit **150** and **160** shown in FIGS. 4 and 6). As noted above, the MOSFET **112** is used to control the discharging of the clamping capacitor **110**. The waveform **121** illustrates the voltage across the primary winding **118** of the isolation transformer **114** as the energy from the clamping capacitor **110** is being recovered. The waveform **123** illustrates the current flowing through the diode **124** back to the input node **52**, while the waveform **125** illustrates the current flowing through the diode **122** back to the input node **52**.

As shown in the waveforms **115** and **117**, the voltage across the clamping capacitor **110** increases slightly when the switch **92** is turned off (shown in waveform **115** when the voltage across the switch **92** rises). Further, it should be noted that any voltage spikes or ringing across the switches **92** and **100** are relatively small due to the energy being captured by the clamping capacitor **110**.

As shown in the waveform **119**, control circuitry applies a positive voltage to the gate of the MOSFET switch **112** for a predetermined time after the MOSFETS **92** or **100** begin conducting again (i.e., when the voltage in the waveform **115** falls back to zero). This has the effect of inducing a positive voltage on the primary winding **118** of the transformer **114** (shown in waveform **121**), which in turn induces a current through the diode **124** (shown in the waveform **123**) which returns the captured energy to the input node **52**. Then, when the switch **112** is turned off by the control circuitry, a relatively small negative voltage is induced in the primary winding **118** of the transformer (waveform **121**), which in turn induces a relatively small current (a few mA) through the diode **122** (waveform **125**). As noted above, the current through the diodes **122** and **124** is returned back to the input node **52** of the power converter **50**, thereby reducing the power loss and increasing the efficiency of the power converter **50**.

FIG. 4 illustrates the power converter **50** also shown in FIG. 2, and further illustrates a control circuit **150** that may be utilized to control the opening and closing of the switch **112**. It is noted that for simplicity, not all components of the power converter **50** shown in FIG. 2 are shown in FIG. 4, but it should be appreciated that the components not shown in FIG. 4 may still be actually present in the power converter **50**.

Generally, the control circuit **150** is operative to turn on the switch **112** for a short, predetermined period of time after the voltage across the MOSFETS **92** or **100** has dropped to approximately zero (e.g., after the MOSFETS **92**, **100** transition from a non-conducting stage to a conducting stage; see waveform **115** in FIG. 3). To achieve this functionality, the control circuit **150** may include diodes **126** and **128** having their anode terminals coupled to the drain terminals of the MOSFETS **92** and **100**, respectively, and the cathode terminals of the diodes **126** and **128** connected to a gate terminal of a MOSFET **138** through a voltage divider (i.e., resistors **134** and **136**). The resistance values for the resistors **134** and **136** may be chosen such that a voltage potential sufficient to turn on the MOSFET **138** is present when the voltage across either of the MOSFETS **92** and **100** is high. In this regard, when the MOSFETS **92**, **100** are not conducting, the MOSFET **138** is conducting or “turned on.”

The control circuit **150** also includes a charging capacitor **142** that has one plate coupled to the drain terminal of the MOSFET **138** and to a voltage source **130** (Vcc) through a resistor **140**. Further, the other plate of the charging capacitor **142** is coupled to the gate terminal of the MOSFET **112**, and to ground through a resistor **146** and a diode **144** that are configured in parallel to each other.

In operation, the charging capacitor **142** is used to control the “on time” of the MOSFET **112**. Initially, the voltage across the charging capacitor **142** is zero when the MOSFET **138** is conducting (e.g., when either of the MOSFETS **92**, **100** are non-conducting, an their drain to source voltage is high). When the MOSFETS **92**, **100** transition to a non-conducting stage, the voltage at the gate terminal of the MOSFET **138** drops to zero, and the MOSFET **138** becomes non-conducting. This causes a current to flow from the voltage source **130** (Vcc) through the resistor **140**, through the charging capacitor **142**, through the resistor **146**, to the ground node **106**. The resistors **146** and **140** may be chosen such that the voltage at the gate terminal of the MOSFET **112** is sufficient to turn on the MOSFET **112** as the charging capacitor **142** is charging. As can be appreciated, the charging capacitor **142** will charge at a rate determined by the RC time constant, and the voltage at the gate terminal of the MOSFET **112** will eventually fall to level that turns the MOSFET **112** off. In this regard, the MOSFET **112** will be turned on for a predetermined period of time that is triggered by the MOSFETS **92**, **100** transitioning from a conducting stage to a non-conducting stage (see the waveforms **115** and **119** shown in FIG. 3).

Then, the above process will repeat each switching cycle so that the MOSFET **112** is turned on for a short period of time each cycle to permit energy stored in the clamping capacitor **110** to be transferred back to the input of the power converter **50** via the isolation transformer **114**. To ensure that the charging capacitor **142** discharges fully each cycle, the diode **144** is coupled between the capacitor **142** and ground **106**.

FIG. 5 demonstrates the ability of the present energy recovery snubber to clamp voltages so as to reduce voltage spikes and ringing effects. The top figure shows a voltage waveform **152** appearing across a synchronous rectifier using a passive, resistive-capacitive (R-C) snubber circuit. The bottom figure shows a voltage waveform **154** appearing across a synchronous rectifier when the present energy recovery snubber circuit is employed. As can be seen in FIG. 5, the voltage spike and ringing are substantially reduced using the present energy recovery snubber circuit.

FIG. 6 illustrates the power converter **50** also shown in FIG. 2 and FIG. 4, and further illustrates a control circuit **160** that may be utilized to control the opening and closing of the switch **112**. As with FIG. 4, it is noted that for simplicity, not

all components of the power converter **50** shown in FIG. 2 are shown in FIG. 6, but it should be appreciated that the components not shown in FIG. 6 may still be actually present in the power converter **50**.

The control circuit **160** is similar to the control circuit **150** shown in FIG. 4, except that an inverter **162** has replaced the MOSFET **138** and the resistor **140** coupled to the voltage source **130** (Vcc). In operation, when the rectifying MOSFETS **92**, **100** are in a non-conducting stage, the charging capacitor **142** has zero voltage potential across its terminals because the input of the inverter **162** is high, while the output, which is coupled to the capacitor **142**, is low. Then, as the voltage at the input of the inverter drops to zero when the MOSFETS **92**, **100** transition to a conducting stage, the output of the inverter **162** becomes high, thereby charging the capacitor **142** and turning on the switch **112**. Similar to the control circuit **150** shown in FIG. 4, the switch **112** remains on for a period of time determined by the RC time constant of the capacitor **142** and the resistor **146**. Additionally, the diode **144** is provided to ensure that the charging capacitor **142** is fully discharged each switching cycle.

As can be appreciated, the conduction period of the MOSFET **112** shown in FIGS. 2, 4, and 6 may be controlled by selecting appropriate values for the charging capacitors and associated resistors. Generally, it is desirable for the MOSFET **112** to remain on for a time period that allows the energy captured by the clamping capacitor **110** during the switching cycle to be recovered. In this regard, the voltage potential across the clamping capacitor **110** will remain relatively steady over time.

It should be appreciated that the embodiments described herein are exemplary and that the various features may be applicable in numerous applications. For example, various types of transformers, switches, or other components may be used. Further, the features described herein may be used with other types of power converters, such as AC-DC power converters. Additionally, in addition to a full bridge DC-DC converter, the features described herein may be used with other configurations including push-pull converters, half-bridge converters, forward converters, and the like.

While the invention has been illustrated and described in detail in the drawings and foregoing description, such illustration and description is to be considered as exemplary and not restrictive in character. For example, certain embodiments described hereinabove may be combinable with other described embodiments and/or arranged in other ways (e.g., process elements may be performed in other sequences). Accordingly, it should be understood that only the preferred embodiment and variants thereof have been shown and described and that all changes and modifications that come within the spirit of the invention are desired to be protected.

What is claimed:

1. An energy recovery snubber circuit for use in a switching power converter having an input and an output, the power converter comprising a first transformer having a primary winding and a secondary winding, a controllable switch coupled to the primary winding, and rectification circuitry coupled to the secondary winding, the energy recovery snubber circuit comprising:

- a voltage clamping element coupled to the rectification circuitry;
- a capacitive element coupled to the voltage clamping element for storing energy captured by the voltage clamping element;
- a second transformer having a primary winding coupled to the capacitive element and a secondary winding coupled to the input of the power converter; and

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control circuitry operably connected to the rectification circuitry, wherein the rectification circuitry triggers the control circuitry to, independent of the amount of energy stored by the capacitive element, selectively cause energy stored by the capacitive element to transfer to the input of the power converter via the second transformer.

2. A circuit as defined in claim 1, wherein the power converter includes a low-pass filter at the output thereof.

3. A circuit as defined in claim 2, wherein the low-pass filter includes an output inductor and an output capacitor.

4. A circuit as defined in claim 1, wherein the power converter includes a rectifier coupled to the secondary winding of the energy recovery snubber circuit.

5. A circuit as defined in claim 1, wherein the rectification circuitry includes a rectifying switch.

6. A circuit as defined in claim 5, wherein the rectifying switch includes a MOSFET.

7. A circuit as defined in claim 1, wherein the controllable switch includes four different switches, two of which are on at a time, one pair of which are on while the other pair is off and one pair of which is off while the other pair is on.

8. A circuit as defined in claim 7, wherein the rectification circuitry includes a first and a second rectifying switch, one of which is on at a time, the first rectifying switch being on when the one pair of switches in the controllable switch are on and the second rectifying switch being on when the other pair of switches in the controllable switch are on.

9. A circuit as defined in claim 8, wherein the first and second rectifying switches include a MOSFET.

10. A circuit as defined in claim 1, wherein the voltage clamping element includes one or more diodes and the control circuitry includes an inverter.

11. A switching power converter having an input and an output, the power converter comprising:

a first transformer having a primary winding and a secondary winding;

a controllable switch coupled to the primary winding;

rectification circuitry coupled to the secondary winding; and

an energy recovery snubber circuit for the switching power converter, the energy recovery snubber circuit comprising:

a voltage clamping element coupled to the rectification circuitry;

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a capacitive element coupled to the voltage clamping element for storing energy captured by the voltage clamping element;

a second transformer having a primary winding coupled to the capacitive element and a secondary winding coupled to the input of the power converter; and

control circuitry operably connected to the rectification circuitry, the rectification circuitry triggers the control circuitry to, independent of the amount of energy stored by the capacitive element, selectively cause energy stored by the capacitive element to transfer to the input of the power converter via the second transformer.

12. A circuit as defined in claim 11, wherein the power converter includes a low-pass filter at the output thereof.

13. A circuit as defined in claim 12, wherein the low-pass filter includes an output inductor and an output capacitor.

14. A circuit as defined in claim 11, wherein the power converter includes a rectifier coupled to the secondary winding of the energy recovery snubber circuit.

15. A circuit as defined in claim 11, wherein the rectification circuitry includes a rectifying switch.

16. A circuit as defined in claim 15, wherein the rectifying switch includes a MOSFET.

17. A circuit as defined in claim 11, wherein the controllable switch includes four different switches, two of which are on at a time, one pair of which are on while the other pair is off and one pair of which is off while the other pair is on.

18. A circuit as defined in claim 17, wherein the rectification circuitry includes a first and a second rectifying switch, one of which is on at a time, the first rectifying switch being on when the one pair of switches in the controllable switch are on and the second rectifying switch being on when the other pair of switches in the controllable switch are on.

19. A circuit as defined in claim 18, wherein the first and second rectifying switches include a MOSFET.

20. A circuit as defined in claim 11, wherein the voltage clamping element includes one or more diodes and the control circuitry includes an inverter.

21. A circuit as defined in claim 1, wherein the voltage clamping element is directly coupled to the secondary winding of the first transformer between the secondary winding and the rectification circuitry such that the voltage clamping element receives a non-rectified output of the first transformer.

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